44 Holladay Formulas

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Introduction

Jack Holladay has authored over a hundred articles from how to calculate visual acuity to piggyback IOLs to negative dysphotopsia. He has authored numerous book chapters and books. He has been perhaps most tireless in the several hundred scientific presentations he has made, often staying after the lecture to help teach someone with lingering questions. Fortunately, he survived a type 1 aortic aneurysm repair in February 2010 [1]. Unfortunately, as a result, he has retired from clinical practice. Though he is still active in consulting, he has had to limit his involvement in additional projects, such as writing this chapter.

This chapter intends to focus on the two IOL power formulas that bear his name: Holladay 1 and Holladay 2 formulas. The second formula is closely linked to his software, Holladay IOL Consultant (HIC); several of its main features will be mentioned at the end. This chapter will begin with a basic math and science section, followed by a brief history of IOL power formulas until the time of the Holladay 1 formula.

Basic Math and Science

Holladay 1 is a thin-lens vergence formula. This was necessary when IOL power formulas started because the posterior curvature of the cornea could not be clinically measured and IOL companies did not provide any information about IOL physical features. Vergence of light is calculated from the object to image plane by means of well-defined analytical formulas that operate paraxially. Lens thicknessLens thickness is neglected in thin-lens formulas.

The main advantage of a thin-lens formula is simplicity. Both the powers of the cornea and of the IOL are defined by a single number (in diopters, D). A single lens constant can be used to change from one IOL type to another. In regular eyes, these formulas can perform with similar accuracy to more complex models, avoiding some disadvantages: Thick-lens raytracing models require the measurement of the posterior corneal curvature and the front and back radii of the IOL (usually not available). Artificial intelligence formulas require huge amounts of data; they tend to treat unusual eyes as "out-of-bounds," eyes because the algorithm has not yet been exposed to such eyes. In addition, artificial intelligence creates complex "black-box" mathematical formulas that are difficult to comprehend and impossible to write or compute simply.

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A thin-lens formula is one that uses the general vergence formula. This can be calculated from the relationships between the vergence of light on the IOL, the power of the IOL, and the vergence of light on the retina (Fig. 44.1). These are all derived from the definition of vergence, where vergence (diopters) = n/d, where d is the focal distance between the lens and the focal plane, and n is the refractive index for that space.

Basic General Vergence Formula

$$IOL = \frac{1336}{AL - ELP} - \frac{1336}{\frac{1336}{TCP} - ELP} \quad (44.1)$$

If an IOL power is being determined for refraction other than for emmetropia, the following refraction component is added to TCP:

$$\frac{1000}{\frac{1000}{Ref} - Vertex} \quad (44.2)$$

AL is the axial length of the eye (mm). ELP is the effective lens position or location of the principal plane of IOL power (mm). IOL is the optical power of the implanted IOL (D). Ref is the postoperative refraction at the spectacle plane (D). Vertex is the spectacle back vertex distance (mm), and TCP is the total corneal power (D). Note that total corneal power does not refer to any specific company's calculation for corneal power.

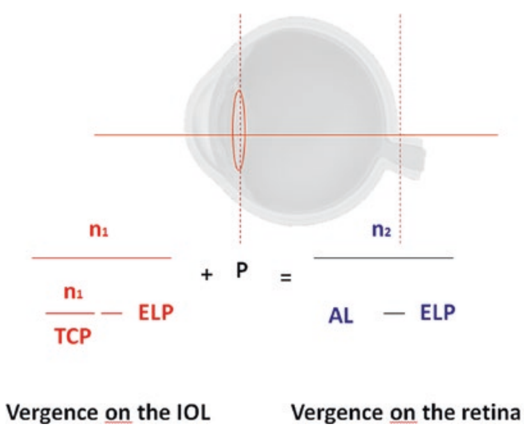

Fig. 44.1 Vergence of light on the retina is equal to the vergence on the IOL plus the IOL power (P). Effective lens position (ELP) is the distance from the cornea to the IOL, TCP is the total corneal power (diopters); AL is the axial length; and n1 and n2 are the indices of refraction of aqueous and vitreous, respectively. From this equation, IOL power can be easily calculated

A thin-lens formula is not necessarily inferior to a thick-lens formula, as long as all variables are correctly defined and the eye fulfills the conditions of paraxial optics. Unfortunately, assumptions and fudge factors have been used in all formulas because physiological accuracy has not yet been realized: Keratometry K value assumes a certain anterior-to-posterior curvature ratio when an arbitrary corneal index of refraction is used to take into account the posterior corneal power (like the corneal standard index of refraction 1.375), and the exact AL is still uncertain (see axial length chapter of this book). Because of these non-physiologic components in the thin-lens formula, the ELP is best considered an imaginary location in space that makes the formula predictions work.

The general vergence formula (GVF) needs only five variables (for the rest of this chapter, vertex distance will be considered a constant, such as 12 mm and not a variable): AL, ELP, IOL, TCP, and ref. The GVF can be manipulated to solve for any one of its five variables. Because ELP is in the denominator twice, some of the calculations can be complex. For simplicity, a box will be used instead of the actual calculations. Box 44.1 solves for the ideal IOL power, given a desired post-op refraction, and Box 44.2 solves for the desired refraction, given an IOL power.

Incorporated into the ELP is a lens constant that moves the ELP anteriorly or posteriorly, depending on the value. Every thin-lens formula works this way. When a desired post-op refraction is entered into most IOL calculators, they first use box 1 to determine the ideal IOL. They then choose a few adjacent available IOL powers, plug them into box 2, and give the predicted refraction for several IOL options.

Hoffer Q, Haigis, SRK/T, T2, and Holladay 1 and Holladay 2 all use the same box. The only

Box 44.1

IOL = [AL TCP ELP Ref]

Box 44.2

Ref = [AL TCP ELP IOL]

differences are created by changes in TCP, AL, and ELP.

Brief History of IOL Power Formulas

Initially, there were no IOL power formulas. An 18-diopter IOL was placed (anterior to the iris) in every patient after cataract surgery. In 1967, Fyodorov published a method to choose individualized IOLs in the Russian literature [2]. In 1973, Colenbrander [3] published this ELP to go in the basic GVF:

$$\mathrm{ELP} = (\mathrm{ACD} - 0.05) \tag{44.3}$$

In 1975, Fyodorov submitted this concept to the English literature [4].

$$\mathrm{ELP} = r - \sqrt{\left(r^2 - \frac{(HWTW + 1)^2}{4}\right)} \tag{44.4}$$

where r is the corneal radius and HCD is the horizontal CD or corneal diameter.

In 1981, Binkhorst 2 introduced axial length into the ELP calculations.

$$\mathrm{ELP} = \left(\frac{Minimum\ of\ 26\ or\ AL}{23.45}\right) \times ACD \tag{44.5}$$

To determine ELP, Colenbrander used an unadjusted measurement of the ACD, Fyodorov used corneal measurements, and Binkhorst 2 modified ELP based on AL [5]. In 1988, Holladay published the first of his two formulas giving way to the third generation of vergence thin-lens formulas [6] being the first to use both axial length and Ks to compute the ELP. Two years later, the SRK/T [7] [8] came out, also using both axial length and Ks in Fyodorov's square root ELP function.

Holladay 1 Formula

It is important to acknowledge that this formula was completely disclosed in Holladay's paper because it has allowed readers to understand the details of the whole process. The main innovation of the Holladay 1 formula was the ELP calculating algorithm based on two predicting variables: AL and K. His formula can be decomposed as the sum of three values (Fig. 44.2):

$$\mathrm{ELP} = \mathrm{Corneal\ thickness} + \mathrm{Corneal\ height}(\mathrm{H}) + \mathrm{Surgeon\ factor}(\mathrm{sf})$$

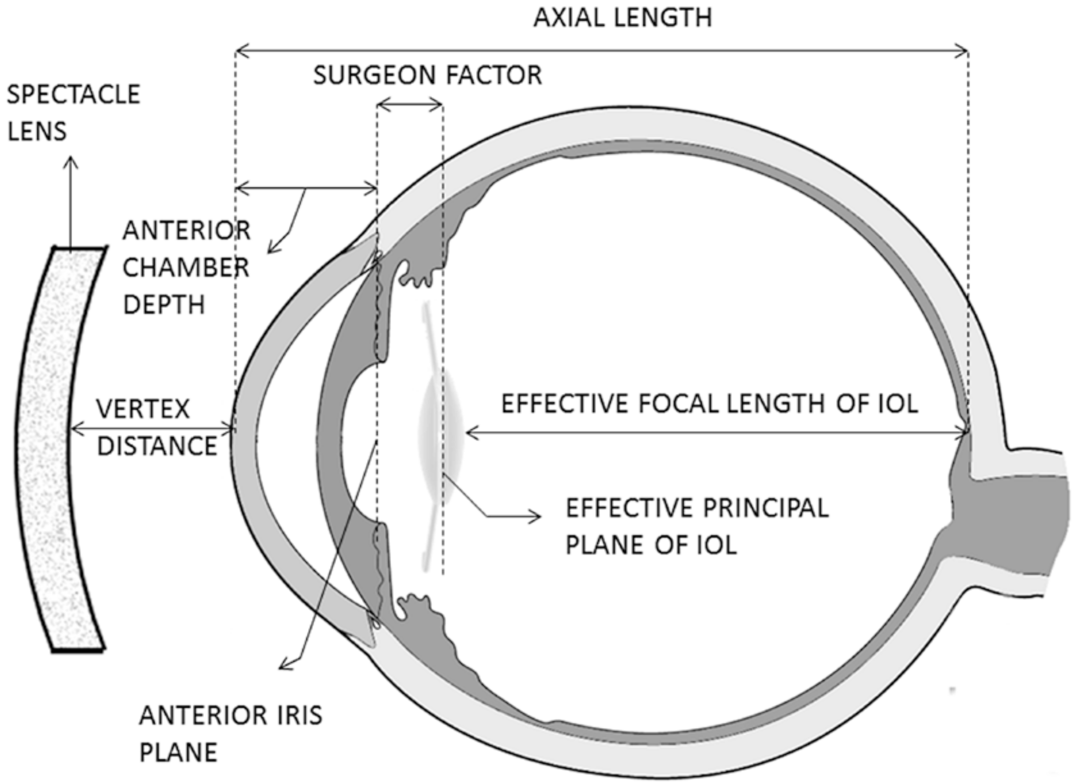

Fig. 44.2 Significant distances for IOL power calculation. Adapted from Holladay's paper [6]

Corneal thickness is a constant: 0.56 mm.

Corneal height (H) is the distance from the endothelium to the iris plane. It was calculated using the equation that calculates the height of a dome previously used for the same task by Fyodorov.

$$\mathrm{H} = r - \sqrt{\left(r^2 - \frac{A^2}{4}\right)} \quad (44.6)$$

where r is the radius of curvature of the cornea and A is the corneal diameter. One clever consideration was to limit the values under the square root so that the value could never be negative value. This was achieved by limiting functions both for r and A, which will become rag and AG:

$$\mathrm{rag} = r, if\ r < 7, then\, rag = 7 \quad (44.7)$$

$$\mathrm{AG} = \frac{12.5 \times AL}{23.45}, if\ AG > 13.5, \\ then\ AG = 13.5 \quad (44.8)$$

where AL is the measured axial length of the eye. As a consequence of these functions, the rag will never be lower than 7 mm and the corneal diameter will never be higher than 13.5 mm. With these modifications, the corneal height equation becomes

$$\mathrm{H} = rag - \sqrt{\left(rag^2 - \frac{AG^2}{4}\right)} \quad (44.9)$$

The sum of corneal thickness and corneal height yields the anterior chamber depth (ACD), defined by Holladay as the distance from the corneal vertex to the anterior iris plane.

The surgeon factor (sf) is the distance from the iris plane to the principal plane of IOL. However, even if this value represents that physical magnitude, Holladay proposed that it should be used as an adjustment factor to take account of any bias of the calculation process: biometer, keratometer, refraction accuracy, surgical technique, etc. In his paper, he also proposed a set of

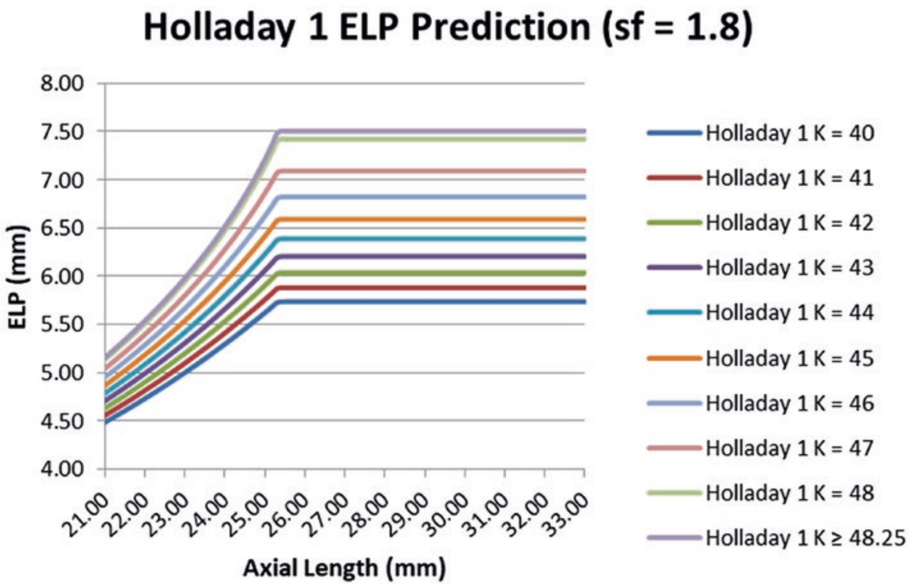

Fig. 44.3 ELP prediction as a function of AL for different average K values. It can be seen that for each K value, the ELP increase stops once the AL = 25.32 mm. In addition, all average Ks steeper than 48.5 D have identical ELP curve. *ELP* effective lens position

equations to back-calculate sf from the refractive results in order to personalize this factor for each surgeon in the article's appendix.

The final ELP equation becomes

$$ELP = 0.56 + rag - \sqrt{\left(rag^2 - \frac{ag^2}{4}\right)} + sf \quad (44.10)$$

It is interesting to graph this ELP function to better understand its behavior with different combinations of AL and K: For any K value, ELP arrives at a maximum value at AL = 25.32 mm; this maximum will increase as K increases until a threshold value of 48.25 D is reached. From then on, the ELP is at its maximum value. Figure 44.3 represents one such plot, where sf = 1.8.

As has been explained, capping of the ELP is the result of limiting the values of A and r in the corneal height (H) equation (Eq. 44.6) to avoid a negative number under the square root, but this can lead to some incorrect predictions in the real world: large anterior segments (e.g., megalocornea) where the IOL could settle very deep in the eye, probably would not predict correctly with this algorithm. In some keratoconus eyes, high K values create this ELP limit, while, in contrast, the SRK/T tends to overestimate ELP, which fortuitously compensates for the abnormal anterior/posterior ratio of these eyes minimizing the hyperopic refraction trend of the Holladay 1.

Beyond the ELP equation, the Holladay 1 formula included a modification for AL and total corneal power (TCP): AL = al + 0.2. A retinal thickness constant value of 0.2 mm is added to the measured AL: TCP = 1000/(3 × r). This equation means that TCP is recalculated from the K measured by the keratometer, which is based on the standard keratometric index of refraction, 1.3375, to a value where the corneal index of refraction is the same value proposed by Binkhorst: 4/3.

Holladay 2 Formula

The Holladay 2 is identical to the Holladay 1 formula except for the ELP calculations [9]. The Holladay 2 ELP algorithm uses more predictors than AL and Ks. It also uses anatomic anterior chamber depth (ACD), lens thickness (LT), corneal diameter or horizontal CD (HCD), pre-op refraction, and age. Surgeons were initially asked to use a metal gauge device to measure HCD for the Holladay 2 formula. It was about half the size of a credit card and had various half-circles drawn on an edge. The surgeon was to match the half-circle to the circle of the cornea. Obviously, when the IOLMaster was able to also measure HCD along with ACD, LT, and AL, this was a welcomed improvement by surgeons who used the Holladay 2 formula.

This formula has not been published and is only available within the software Holladay IOL Consultant® and in different biometry and corneal topography devices. It is adapted to perform calculations in particular situations such as eyes that have undergone previous corneal refractive surgery where an alternative K value can be calculated with different methods. Afterward, the Holladay 2 formula will be used in a double-K manner to avoid the ELP estimation error (see the dedicated chapter in this book). In eyes filled with silicone oil or with a scleral buckle, the calculation is automatically adjusted. The toricity of the IOL is also calculated as described by Holladay in 2019. It is the difference between the postoperative refractive astigmatism in the corneal plane and the preoperative keratometric astigmatism [10]. This will empirically compensate for any of the following involved factors: posterior corneal astigmatism, IOL tilt and decentration, and any unknowns. The toric conversion from the corneal plane to IOL will be a function of ELP and IOL power as calculated by the formula.

Axial Length Adjustment

Holladay 1 was designed with ultrasound. It has suffered prediction accuracy at extreme axial lengths. Recently, it has been suggested that perhaps the switch from immersion, segmental ultrasound to optical biometry was at least partially responsible [11]. When optical biometry was modified to produce sum-of-segments axial length, these ultrasound-derived formulas did much better, for both long and short eyes, than when conventional optical biometric axial lengths were used. A modified sum-of-segments axial length, CMAL, was shown in one paper to improve both Holladay 1 and Holladay 2 at extreme axial lengths [12].

After co-authoring a paper that studied formula predictions with two large databases developed by Kaiser Permanente [13], Jack Holladay used those eyes to re-calibrate optical biometry AL for long eyes. He regressed to the ideal back-calculated axial lengths, which made the Holladay 1 and Holladay 2 formulas improve. Rather than a simple linear regression, he used a polynomial nonlinear regression [14]. The advantage of this over CMAL is that it does not require lens thickness.

These are the formulas proposed by Holladay to adjust the AL when its value is >24 mm:

$$\begin{aligned} \mathrm{AL}(\text{Holladay 1 formula}) = {} & 0.0000462655^{*}\,\mathrm{A2}^{\wedge}5 - 0.0070852534^{*}\,\mathrm{A2}^{\wedge}4 + 0.4320542309^{*}\,\mathrm{A2}^{\wedge}3 \\ & - 13.1162616532^{*}\,\mathrm{A2}^{\wedge}2 + 199.1238629431^{*}\,\mathrm{A2} - 1190.3984759734 \end{aligned}$$

$$\begin{aligned} \mathrm{AL}(\text{Holladay 2 formula}) = {} & -0.0001154786^{*}\,\mathrm{A2}^{\wedge}3 + 0.0032939472^{*}\,\mathrm{A2}^{\wedge}2 \\ & + 1.001040305^{*}\,\mathrm{A2} - 0.3270056564 \end{aligned}$$

where A2 is the AL measured by the optical biometer (non-segmented measurement).

Formula Performance

Holladay 1 has performed well through the years. Being a mainstay for standard-length eyes since a paper in 1993 [15] where Hoffer found that Hoffer Q was ideal in short eyes, SRK/T was ideal in long eyes, and Holladay 1 was ideal for the bulk of the eyes in the middle.

Though results are similar, Holladay 1 tends to outperform Holladay 2 for normal-length eyes. The value of Holladay 2 improves greatly for longer eyes, especially when AL is adjusted. Perhaps hundreds of studies have compared these formulas. A few of the larger ones were selected to highlight the results.

Aristodemou et al. [16] studied Hoffer Q, Holladay 1, or SRK/T in 8108 eyes after cataract surgery, evaluating more than one IOL model. His group found that Holladay 1 had the best mean absolute error for eyes from 23.50 mm to 25.99 mm.

Another study of 1079 eyes, of 1079 patients, compared results of eyes measured with (Lenstar data) and without (IOLMaster 500 data) lens thickness [17]. Holladay 1 was better than Holladay 2, SRK/T, and Hoffer Q. However, when LT was added as a variable in these same eyes, Holladay 2 became the best of these formulas.

A paper by Kane et al [18] compared 3241 patients. Following the general rule, for medium (AL > 22.0 mm to <24.5 mm) and medium long (AL ≥ 24.5 to <26.0 mm) eyes, Holladay 1 was once again the best of these four formulas, but the Holladay 2 was better for the long eyes (> 26 mm). Note that the actual differences among these formulas were quite small. The maximum difference in mean absolute error between Barrett and T2, SRKT, and Haigis was about 0.08 diopter (Fig. 44.4).

In the previously mentioned Kaiser Permanente study [13], Melles studied two IOL models in 18,501 eyes from 18,501 patients. The Holladay 2 had the lowest standard deviation of these four formulas, but only slightly better than Holladay 1. When the original Wang-Koch long-eye adjuster was applied to Holladay 1, it became the best of all these formulas.

In an update of this study [19], a subgroup analysis of 13,301 eyes with SN60WF implants showed that in all breakdowns of eyes with axial lengths over 22.5. Holladay 2 was better than Holladay 1, Hoffer Q, and SRK/T. For eyes between 22.5 and 25.5, Holladay 1 was better than Hoffer Q and SRK/T, but for eyes longer than 25.5, SRK/T was the best of these three formulas.

None of the prior studies used the Holladay 1 or 2 formulas with the updated nonlinear regression AL. In 2019, a study of 10,930 eyes from the UK National Health Services evaluated Holladay 2 using the updated formula with nonlinear regression AL [20]. It compared 9 IOL power formulas, ranking them by mean absolute error. The authors found the Holladay 2 to be the second-best formula for short eyes (≤ 22.00 mm) and for long eyes (≥ 26.00 mm).

In Tables 44.1 and 44.2, the outcomes of Holladay 1 and Holladay 2 published in the last 5 years are presented.

Holladay IOL Consultant Software.

The Holladay HIC program has several helpful additions beyond merely containing the

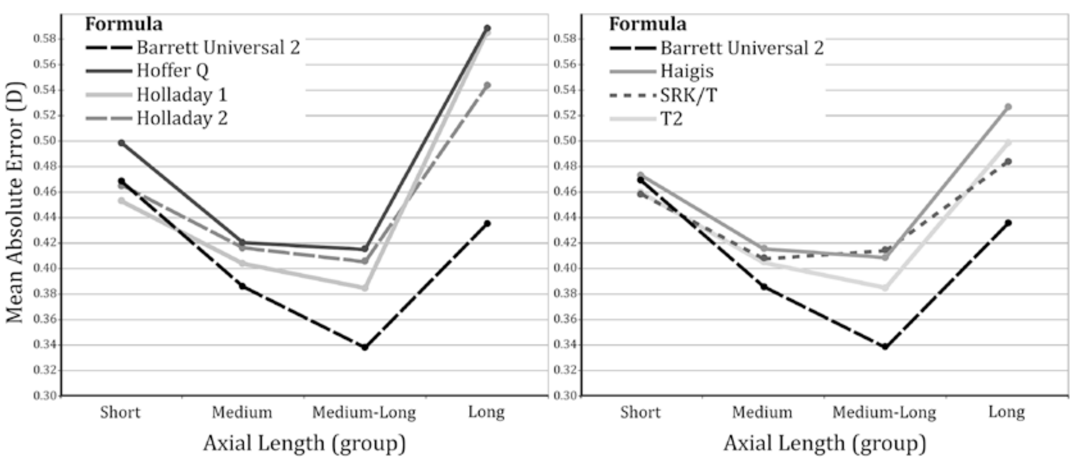

Fig. 44.4 (From Kane paper [18]) Mean absolute error plotted against AL groups for the Barrett Universal II, Hoffer Q, Holladay 1, Holladay 2, Haigis, SRK/T, and T2 formulas. Formulas were grouped to allow easier visualization

Table 44.1 Holladay 1 formula outcomes in recently published papers. IOLM: IOLMaster. SD: standard deviation

First author	Year	Mean	SD	MAE	MEDAE	% in ±0.50 D	% in ±1.00 D	N
Cooke [17] (Lenstar)	2016	0.00	0.408	0.320	0.268	79.1	98.6	1079
Cooke [17] (IOLM 500)	2016	0.00	0.414	0.326	0.270	79.5	98.4	1079
Kane [18]	2016	0.00	n.a.	0.408	0.326	69.4	99.6	3241
Kane [21]	2017	−0.01	n.a.	0.398	0.321	70.1	94.3	3122
Næser [22]	2019	−0.06	0.36	0.290	0.250	85.0	100.0	151
Melles [13]	2018	0.00	0.453	0.351	0.287	75.0	96.8	18,501
Melles [13] (W-K)	2018	0.00	0.439	0.340	0.275	76.6	97.2	18,501
Darcy [20]	2020	0.00	0.512	0.397	0.321	69.6	94.4	10,930
Taroni [23]	2020	0.00	0.382	0.298	0.257	82.4	98.9	101
Hipolito-Fernandes [24]	2020	0.00	0.461	0.361	0.299	74.3	96.1	828
Tsessler [25] (Lenstar)	2021	0.02	0.38	0.29	0.21	81.0	98.0	153
Tsessler [25] (IOLM 700)	2021	−0.05	0.37	0.29	0.24	80.0	100.0	153
Tsessler [25] (IOLM 700 + TK)	2021	0.02	0.38	0.29	0.24	80.0	98.0	153

MAE mean absolute error, *MEDAE* median absolute error, *W-K* Wang-Koch AL correction, *TK* total keratometry by IOL Master 700, *n.a.* not available

Table 44.2 Holladay 2 formula outcomes in recently published papers

First author	Year	Mean	SD	MAE	MEDAE	% in ±0.50 D	% in ±1.00 D	N
Cooke [17] (Lenstar) Presurg ref	2016	0.00	0.423	0.336	0.288	76.6	98.4	557
Cooke [17] (IOLM 500) Presurg ref	2016	0.00	0.432	0.346	0.297	75.2	98.1	557
Cooke [17] (Lenstar) no ref	2016	0.00	0.404	0.318	0.261	79	98.1	557
Cooke [17] (IOLM 500) no ref	2016	0.00	0.417	0.331	0.287	79.3	97.7	1079
Kane [18]	2016	0.00	n.a.	0.420	0.341	67.4	99.7	3241
Kane [21]	2017	−0.01	n.a.	0.410	0.337	68.2	94.4	3122
Melles [13]	2018	0.00	0.450	0.350	0.285	75.4	97.0	18,501
Darcy [20]	2020	0.00	0.503	0.390	0.312	71.0	94.9	10,930
Taroni [23]	2020	0.00	0.411	0.322	0.285	82.4	97.8	101
Tsessler [25] (IOLM 700)	2021	−0.18	0.39	0.34	0.28	79	99	153
Tsessler [25] (IOLM 700 + TK)	2021	0.10	0.40	0.33	0.29	78	99	153

IOLM IOLMaster, *SD* standard deviation, *MAE* mean absolute error, *MEDAE* median absolute error, *AL* axial length correction, *TK* total keratometry by IOL Master 700, *n.a.* not available, *Presurg ref.* pre-surgery refraction used in the calculation, *No ref.* pre-surgery refraction not used in the calculation

Holladay 2 formula. There is a complete set of options to address most of the situations found in the clinical practice: post-LASIK and post-RK eyes, silicone-filled eyes, scleral buckle, keratoconus, etc. Calculation of the IOL power can be adjusted for sulcus implantation. The HIC program can use a refractive formula, thereby not needing an AL, for these calculations in either aphakic or pseudophakic eyes: secondary implants, and phakic IOL calculations.

There is a toric pre-op planner menu to perform toric IOL calculations where the IOL placement axis and the expected refraction for the selected lens are clearly displayed (Fig. 44.5a) and a postoperative toric analysis module that calculates the total SIA and the rotation needed to achieve the best possible refraction (Fig. 44.5b). The latter is done by two methods, from postoperative Ks and refraction and from the observed IOL meridian and postoperative refraction, which allows double-checking to detect any incorrect data. These toric calculations are done taking into account the effect of ELP and IOL power by the Holladay 2 formula.

After surgery, two software modules allow the surgeon to study postoperative results: One calculates the postoperative surgically induced refractive change (SIRC) both for refraction values and for keratometry values (Fig. 44.6). The other back-calculates five variables individually from the actual values. These are AL, K, post-op

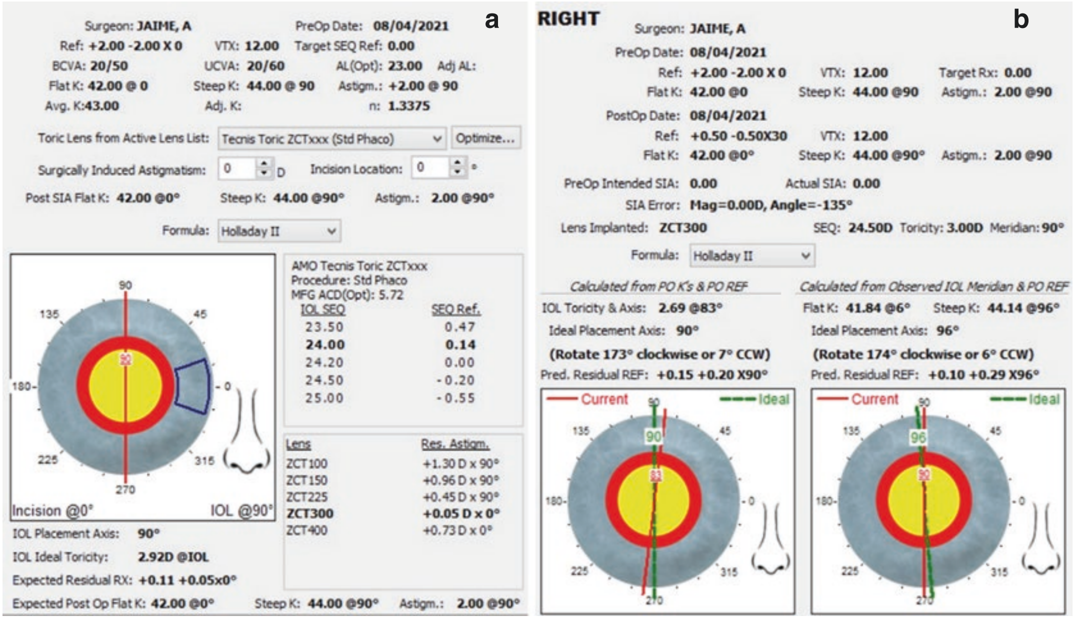

Fig. 44.5 (**a** and **b**)On the left is the toric IOL planner where the toric IOL and the predicted refraction are displayed. On the right is the toric IOL postoperative back calculator where the rotation of the implanted IOL that will yield the minimum astigmatism is calculated by two methods

Rx, IOL power, and IOL constant (Fig. 44.6b). These can be useful to look for the reason for a postoperative refractive surprise as four of these variables can be checked again.

There is a powerful aggregate data analysis tool called surgical outcomes assessment program (SOAP) that offers prediction error analysis allowing for different selection criteria, a complete induced astigmatism study, and IOL constant optimization for SRK/T, Hoffer Q, Holladay 1, and Holladay 2 formulas.

Acknowledgments Many of the references and much understanding of the early formulas were enhanced from this manual: Retzlaff JA, Sanders DR, and Kraff M. Lens Implant Power Calculation A manual for ophthalmologists and biometrists Ed 3. 1990 Slack.

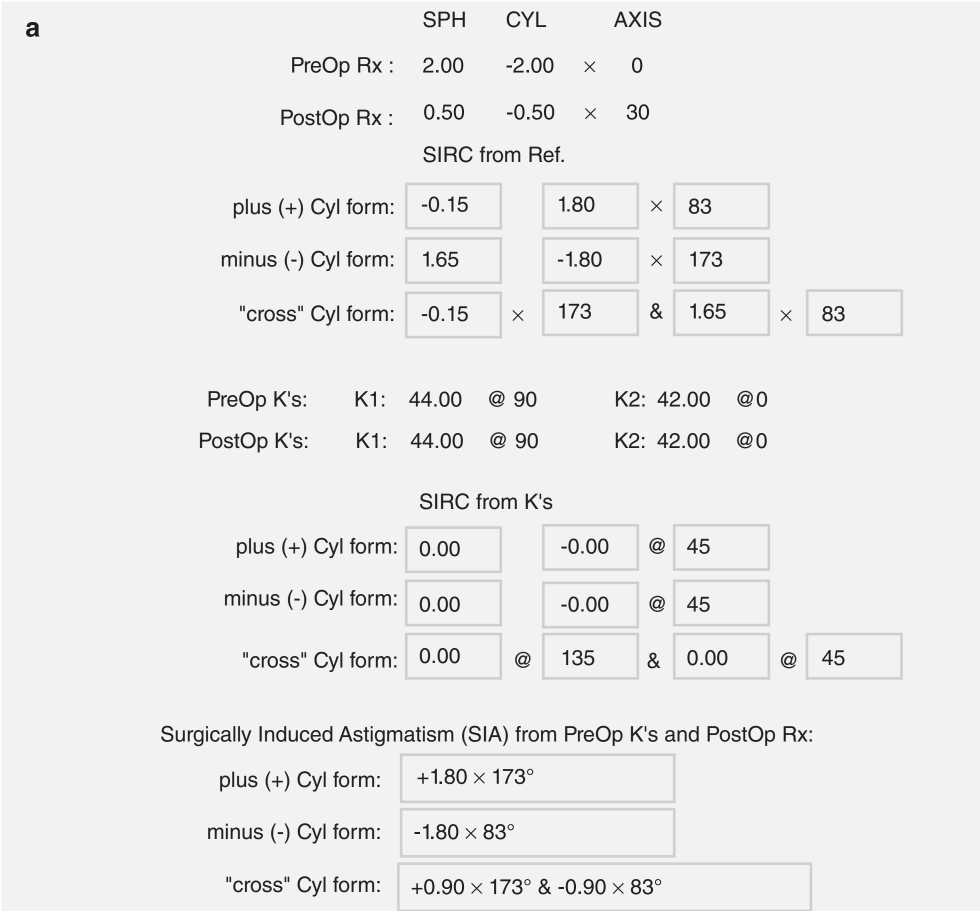

Fig. 44.6 (**a** and **b**)On the left is the surgically induced refractive change (SIRC) calculator. On the right is the postoperative back calculator that is useful to analyze unexpected postoperative refractions

b Actual Values:

Implanted IOL Power SEQ:	24.50		
PostOp SEQ Ref:	0.250	VTX:	12.0
PreOp Adj AL:	23.00		
PreOp Avg K:	43.00		
Lens Constant(LC):	5.724	MFG	

BackCalculated Values (Calculated from 4 measured values)

			From:
IOL Power SEQ:	23.830	D.	(K, AL, LC, Ref)
SEQ Ref:	-0.203	D.	(K, AL, LC, IOL)
Adj AL:	22.808	mm	(K, LC, IOL, Ref)
Avg. K:	42.405	D.	(AL, LC, IOL, Ref)
LC:	6.019		(K, AL, IOL, Ref)
Prediction Error:	-0.453	D.	(Pred Ref - PO Ref)

Fig. 44.6 (continued)

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